

Watt-level continuous-wave emission from a bi-functional quantum cascade laser/detector

Benedikt Schwarz,^{*,†} Christine A. Wang,[¶] Leo Missaggia,[¶] Tobias S. Mansuripur,[§]
Paul Chevalier,[‡] Michael K. Connors,[¶] Daniel McNulty,[¶] Jeffrey Cederberg,[¶]
Gottfried Strasser,[†] and Federico Capasso^{*,‡}

[†]*Institute of Solid State Electronics, TU Wien, 1040 Vienna, Austria*

[‡]*School of Engineering and Applied Sciences, Harvard University, Cambridge, MA 02138,
USA*

[¶]*Lincoln Laboratory, Massachusetts Institute of Technology, Lexington, MA 02420, USA*

[§]*Department of Physics, Harvard University, Cambridge, MA 02138 USA*

E-mail: benedikt.schwarz@tuwien.ac.at; capasso@seas.harvard.edu

Abstract

Bi-functional active regions, capable of light generation and detection at the same wavelength, allow a straightforward realization of the integrated mid-infrared photonics for sensing applications. Here, we present a high performance bi-functional device for 8 μm capable of 1 W single facet continuous wave emission at 15°C. Apart from the general performance benefits, this enables sensing techniques which rely on continuous wave operation, e.g. heterodyne detection, to be realized within a monolithic platform and demonstrates that bi-functional operation can be realized at longer wavelength, where wavelength matching becomes increasingly difficult and that the price to be paid

This material is based upon work supported by the Assistant Secretary of Defense for Research and Engineering under Air Force Contract FA8721-05-C-0002 and/or FA8702-15D-0001. Any opinions, findings, conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the Assistant Secretary of Defense for Research and Engineering.

©2017 Massachusetts Institute of Technology.

in terms of performance is negligible. In laser operation the device has the same or higher efficiency compared to the best lattice-matched QCLs without same wavelength detection capability which is only 30% below the record achieved with strained material at this wavelength.

Keywords

quantum cascade laser, quantum cascade detector, lab-on-a-chip, monolithic integrated photonics

1 Introduction

Integrated photonics is a growing research field and is often connected to silicon photonics at telecommunication wavelength¹ aiming for high speed optical data links or quantum computing.^{2,3} However, integrated photonics enables a much wider field of fascinating applications, e.g. the realization of extremely compact chemical sensing systems. Active optical devices are mostly realized with epitaxial grown III-V materials, which makes their integration on Si particularly difficult. Heterogeneous integration using transfer techniques allows both single device and wafer scale transfers and were utilized to demonstrate III-V lasers⁴ and particularly quantum cascade lasers⁵ integrated on silicon. Also direct growth of III-Vs on silicon is an active research field with some interesting recent results, e.g. the direct growth of a III-V quantum dot laser on a silicon substrate.¹ However, the growth of high quality materials will remain challenging. For many applications, the integration of electronics is not particularly important and III-V substrate based integration would be sufficient. This allows direct high quality growth without the need for wafer bonding. Regardless if grown on Si on InP substrates, III-V growth remains to be the most expensive step during fabrication. Therefore, it is beneficial to keep the required number of growth steps at a minimum. An epilayer material which can be used both as a gain as well as a photodetecting medium

depending on the applied bias, thereby, serves as an ideal solution for photonic integration. Such a bi-functional active medium provides all the features needed to build lasers, detectors as well as modulators.

Moving to longer wavelength, e.g. the mid-infrared fingerprint region, active optical components, such as lasers and detectors, are increasingly difficult to realize, especially when aiming for room-temperature operation. The mid-infrared region is particularly useful, as no other wavelength region can offer the same sensitivity or selectivity for chemical spectroscopy. It even enables selective detection of different isotopes.⁶ The first developments on molecular beam epitaxy by Cho and Arthur⁷ and the demonstration of the quantum cascade laser (QCL) by Faist et al.⁸ significantly pushed the entire field.^{9,10} QCL based spectroscopy was pioneered by several groups who early identified its high potential to realize sensing setups with a smaller footprint.^{11–15} Nowadays, QCLs are commercially available and can be found in a number of different applications.

The capability of quantum cascade structures for photodetection^{16–18} received much less attention, maybe because of the rapid developments of competing technologies, such as MCT detectors¹⁹ and photoconductive quantum well infrared detectors.²⁰ However, the ability of using similar device structures and the same materials to realize lasers or detectors led to the proposal that such structures can potentially be used to realize monolithically integrated devices that serve as a single chip solution for chemical sensing.²¹ The idea is simple, a bi-functional quantum cascade epilayer, which can be used both as a gain as well as photodetection material, serves as a basic building block. Lasers and detector are then realized by patterning this epilayer which covers the entire chip. Finally, together with passive optical elements, a monolithic platform that includes all required optical elements can be realized to downscale mid-infrared laser based sensor systems to a single chip. The realization of such bi-functional devices requires careful band engineering to allow lasing and detection at the same wavelength and further with a decent performance. The first realization in 2012 required a compromise to be taken in terms of a reduced laser performance.²² The demon-

stration of a monolithically integrated sensor using plasmonic waveguide demonstrated that such bi-functional active regions allow a straightforward realization of integrated photonics.²³ More recently, bi-functional active regions have also been used in prototype gas sensing setups aiming for remote sensing.^{24,25} Their practical realization is still strongly limited by the device performance and would greatly benefit from continuous wave operation which enables heterodyne detection schemes.

In this paper, we present significant progress on bi-functional device developments to address remaining challenges. First, the presented device is designed for a wavelength of $8\text{ }\mu\text{m}$ to demonstrate that a bi-functional high performance device can also be realized at longer wavelength, where wavelength matching between the laser and the detector becomes increasingly difficult. Thereby, we show that the flexibility due to the engineerable wavelength known from QCLs to address a variety of different sensing applications also applies to bi-functional devices. Second, we pushed the laser performance to a new level, where our bi-functional device can compete or even outperform conventional QCLs. The device is capable of emitting 1 W single facet output power in continuous wave at 15°C . The achieved wallplug efficiency (WPE) of 12% and 7% in pulsed and continuous wave operation is the equal to or higher than reported values for unstrained material. This clearly shows, that the cost of laser performance due to the additional detection functionality can be negligible.

2 Design considerations

Continuous wave operation requires two main ingredients: A temperature insensitive gain medium with a low threshold and a low loss waveguide with a low thermal resistance. The first QCL capable of room-temperature continuous wave emission was demonstrated in 2001 by Beck et al.²⁷ Since then, the output power and wall-plug efficiency have been significantly improved and watt-level output powers are not unusual anymore.^{28–30} For bi-functional devices the conventional QCL design is modified, such that at zero bias the active transitions

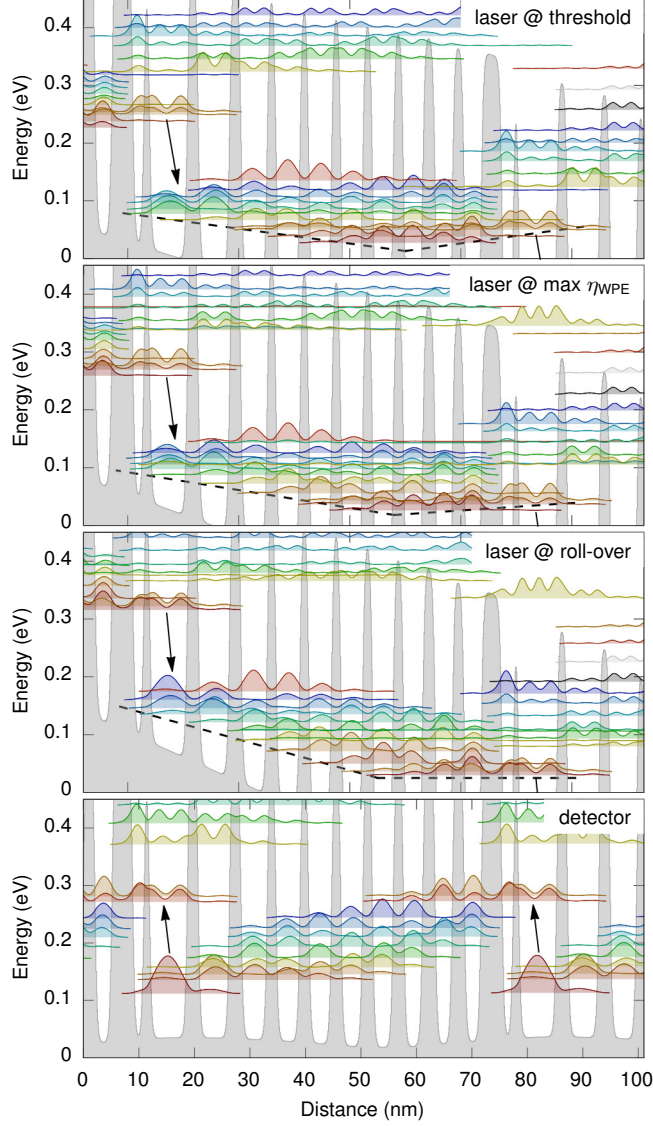


Figure 1: Banddiagram at laser threshold, bias of highest pulsed wallplug efficiency and roll-over as well as at detector bias (zero bias). Graded interfaces due to MOVPE growth are considered in the model. The dashed line indicates the pocket shaped injector.²⁶

can also be used for photodetection at the laser emission wavelength.²² Traditional laser designs, however, show a large spectral shift because the optical transition takes place between the extraction states and the upper laser level. In the first bi-functional designs, wavelength matching was achieved using thicker barriers and reduced energy splittings between the extraction levels, but with the drawback of a reduced laser performance. These devices showed relatively high threshold currents and were restricted to short pulse operation. The introduction of the horizontal-vertical extraction scheme was a significant step to improve

the pulsed laser performance.³¹ As indicated by the name, the extraction from the lower laser level is split into two logical parts. The first part (horizontal extractor) uses 2–3 thick barriers and a reduced coupling to maintain wavelength matching between the laser and the detector. The second part (vertical extractor) uses multiple strongly coupled states to achieve fast LO-phonon scattering and to prevent thermal back-filling, described in more detail in Ref.³¹ The presented device is designed for 8 μm to show that wavelength matching can also be achieved at longer wavelengths. The intrinsic wavelength shift, which should be compensated, becomes more and more pronounced and makes wavelength matching more difficult. This is because the ratio between the photon energy and the splitting between the extraction states, which is usually matched to the LO-phonon energy, increases. Here, we show, that wavelength matching is still possible with the horizontal-vertical extractor design procedure, although we take a small compromise. To maximize the overall performance we accepted a small remaining detuning between the laser spectrum and the peak photoresponse, which slightly reduces the responsivity at the emission wavelength, but allows a better laser performance.

In order to push the device performance to enable a low threshold at high temperatures, we reworked the second part of the injector to achieve an even lower thermal back-filling and more efficient injection. In the literature, the banddiagram of a QCL is commonly plotted for one bias. However, it has to be noted that during the design process it is required to take care of the entire bias region from zero to roll-over to identify undesired current paths and regions of negative differential resistance. Furthermore, aiming for continuous wave operation (in contrast to pulsed operation), it is not particularly useful to optimize the device at the bias where the injector state is aligned with the upper laser level. This situation occurs at the roll-over in pulsed mode, which is above the thermal roll-over in continuous wave. More important for continuous wave operation is to achieve a low laser threshold at high operation temperatures. Thus, we mainly optimized our device for bias conditions slightly above threshold, while assuming a high electron temperature. To give a better insight, we

plot the banddiagram of our design for three selected laser conditions (threshold, highest wallplug efficiency in pulsed mode, roll-over in pulsed mode) as well as for the detector operation at zero bias in Figure 1. Graded interfaces were used in the bandstructure design to model the behavior of the MOVPE growth.³² Interface grading strongly modifies the banddiagram and leads to a red-shift in experiments. Here, we directly considered the grading in our design process via an empirically determined width from the wavelength shift between experiment and simulation of a number of previously grown devices, which later turned out to be consistent with the profiles obtained from atom probe tomography measurements. This approach allows a reliable prediction of the emission wavelength and a more accurate design. A more detailed description of our interface grading model can be found in Ref.³²

Table 1: Table of selected high performance continuous wave QCLs from literature. The values in brackets correspond to pulsed operation. The given values for pulsed and continuous wave correspond to the highest values achieved in the respective operation mode and are not necessarily from the same device geometry. Often narrower ridges have been used for continuous wave operation.

Authors	λ	P	η	T	Type
Maulini et al. ³³	7.1 μm	1.4 W (2.9 W)	10% (19%)	20°C	QCL strained
Lyakh et al. ³⁴	9 μm	2 W (4.5 W)	10% (16%)	20°C	QCL strained
Troccoli et al. ³⁵	9.2 μm	2 W (4.4 W)	10% (16%)	15°C	QCL strained
	7.8 μm	0.8 W (-)	3.4% (-)	15°C	QCL unstrained
	8.9 μm	0.92 W (-)	4.0% (-)	15°C	QCL unstrained
Bismuto et al. ³⁶	8.5 μm	0.45 W (1.1 W)	- (11.5%)	20°C	QCL unstrained
Fujita et al. ³⁷	8.6 μm	0.313 W (6.5 W)	2.74% (10.8%)	30°C	QCL unstrained
Missaggia et al. ³⁸	9 μm	1 W (-)	7% (-)	15°C	QCL unstrained (same facility)
Schwarz et al. ³¹	6.8 μm	- (0.5 W)	- (4.5%)	20°C	QCLD unstrained
This work	8 μm	1 W (1.5 W)	7% (12%)	15°C	QCLD unstrained

The injector is designed in such a way, that it forms a triangularly shaped effective potential. This approach is similar to the so-called pocket injector design.²⁶ Electrons can scatter down into the pocket and the large energy separation minimizes thermal back-filling. We want to emphasize that at laser threshold, the energy distance between the lowest injector ground state and the upper laser level is quite large (26 meV). However, at room-temperature - and keeping in mind that the electron temperature can be much higher than the lattice

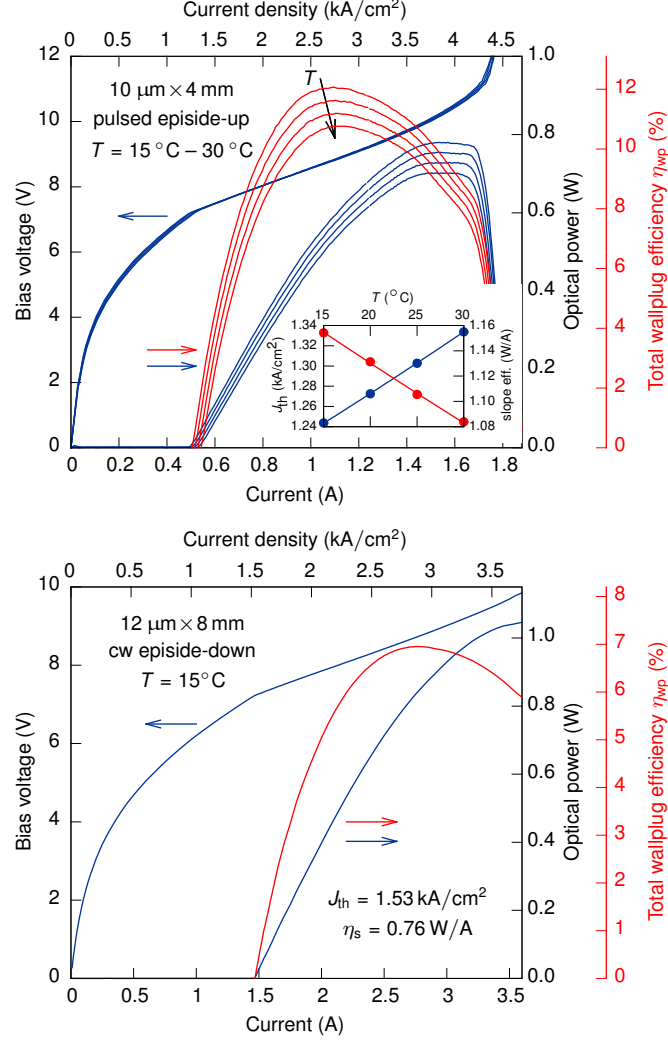


Figure 2: Current, voltage, single facet output power relation as well as total wallplug efficiency (both facets) for an episide-up mounted device in pulsed operation (upper) and an episide-down mounted buried heterostructure device in continuous wave operation (lower). The inset in show the temperature dependence of the threshold current density and slope efficiency in pulsed operation. From this we extract the characteristic temperatures $T_0 = 215 \text{ K}$ and $T_1 = 236 \text{ K}$ via least square fits (solid lines).

temperature in this region due to the emission of off-resonant LO-phonons - thermal excitation is sufficient to achieve population inversion and provides an additional cooling effect for hot electrons. Thus, a quite large part of the voltage drop through the injector is compensated by the required "cooling" energy to inject electrons into the upper laser level (At threshold $70 \text{ meV} - 26 \text{ meV} = 44 \text{ meV}$). The simulation tool used for this work resolves the k-space and thus includes non-equilibrium in-plane distributions.³⁹ The effective potential is

continuously tilted with increasing bias as illustrated by the dashed line in the banddiagrams (see figure 1). The ground state thereby moves from the middle to the right to achieve an increasing direct injection. This allows for an efficient lower laser level depopulation over the entire bias range. At the bias where light generation is the most efficient, the upper laser level is still significantly above the lowest ground state (banddiagram 2). The roll-over in pulsed mode occurs, when the ground state of the injector is in resonance with the upper laser level (banddiagram 3). A further increase in bias would lead to a region of negative differential resistance. Following, domains for different electric field will form in order to maximize current flow and the laser shuts off because of misalignment. A main difference to an injector with one pronounced tunneling level is that the injection current is mainly limited by thermal excitation of hot electrons rather than the tunneling efficiency. The single tunneling level injector does not allow for large cooling effects but might require a slightly smaller doping density. However, it is not obviously clear if a slightly higher doping results in higher loss, as the conventional Drude absorption model for bulk collapses for subband devices. Free-carrier absorption in quantum cascade structures is fundamentally different and becomes very small.⁴⁰ The reduction of the lower laser level population can be expected to give a larger contribution.

The second ingredient for continuous wave operation is a low loss waveguide with a low thermal resistance. This is a main reason, why the highest performance levels were mostly achieved using material systems on InP substrates.^{28–30} InP is an ideal cladding material with low optical loss and high thermal conductivity. In contrast to previous devices we used low doped InP top and bottom cladding layers as well as lateral InP regrowth for better heat extraction.⁴¹ The low optical loss of this waveguide allows a reduction of the active region doping by roughly a factor of two compared to previous bi-functional devices to further reduce the laser threshold.

Both devices, the QCLD and the reference QCL were grown nominally lattice matched ($\pm 0.5\%$ or less strain) on n-InP ($2.5 \times 10^{18} \text{ cm}^{-3}$) substrates by MOVPE in a Veeco D125

multi-wafer reactor. The very same waveguide structure was used and the larger size of one cascade of the QCLD was compensated with a smaller number of periods to obtain the same optical properties of the waveguide geometry. Superlattice regions were included in the QCLD device to minimize series resistances at the first and last period as well as at the InGaAs/InP interfaces for the detector operation. These regions were carefully designed to prevent unintentional resonant absorption. The laser ridges were fabricated by conventional photolithography and dry etching. The devices for pulsed measurements and the on-chip detector characterization were fabricated using SiN passivation, sputtered Ti-Au top contacts and were mounted episcide up. The continuous wave devices were fabricated in the buried heterostructure configuration using lateral Fe-InP regrowth and with Ti-Au contacts on both sides. The buried heterostructure devices were cleaved to single devices and mounted episcide down. The laser performance was characterized with standard equipment, e.g. FTIR, pulser and low noise dc current source, etc. The optical power was measured with a calibrated power meter considering an estimated collection efficiency of 95%, which is consistent with the measurements performed at MIT-LL for this and the comparison QCL devices of Ref.³⁸

3 Results and Discussion: Laser operation

The improvements in the active region design in combination with the optimized waveguide enable bi-functional device with outstanding laser performance. Figure 2 show the light-current-output power relation for two devices. The episcide-up mounted device shows an excellent pulsed performance with a total wallplug efficiencies of 12%. The inset shows the temperature dependence of the threshold current density and slope efficiency, from which we extract the characteristic temperatures $T_0 = 215$ K and $T_1 = 236$ K, respectively. High characteristic temperatures are crucial for high temperature operation. The second sample is a longer buried heterostructure device, which was mounted episcide-down on a water cooling block without Peltier element. It is capable to emit 1 W single facet output power

in continuous wave at 15°C cooling water temperature and achieves a maximum wallplug efficiency of 7%. Both the pulsed and continuous wave performance are excellent when compared to record values from literature. Table 1 summarizes published power and efficiency record values for the emission wavelengths around 8 μm . The achieved wallplug efficiencies are just 30% smaller compared to the highest published records at this wavelength. One has to note, that these record values were achieved with conventional QCLs without same wavelength detection functionality using strained materials. It has been extensively discussed that strained materials have a significant advantage to realize efficient devices.^{42,43} Unstrained devices suffer from carrier leakage because of the relatively small band-offset, where in well designed strained devices carrier leakage can be neglected at such long wavelength. Compared to QCLs based on unstrained materials, our device outperforms most published results and performs similar compared to QCLs from the same facility. This clearly demonstrates that the additional detection functionality is not necessarily connected to a performance drawback.

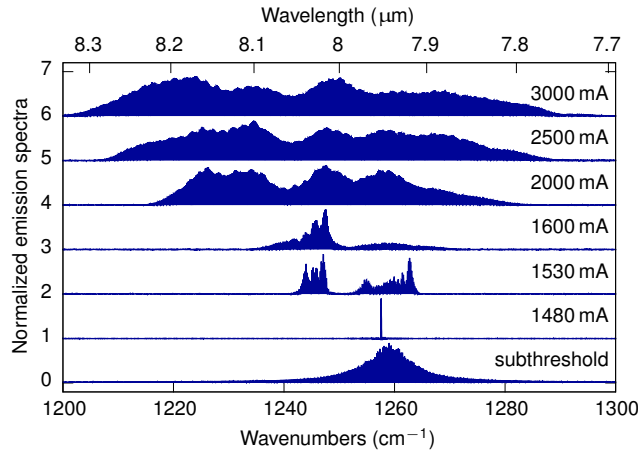


Figure 3: Emission spectra of the episcide-down mounted QCLD in continuous wave operation. The shown spectral evolution is typical to QCLs: At threshold the laser starts at a single mode and then switches to a dense spectrum, where all Fabry-Perot modes laser, with growing bandwidth. Other than known from our lasers, the dense spectrum even occurs close to threshold after some minutes.

The emission spectrum in continuous wave is shown in figure 3. Starting from single mode at threshold, the spectrum switches very early to the dense mode, where all Fabry-

Perot modes are occupied. This is a hint of a strong four-wave mixing process and low dispersion in this device. At higher currents the spectrum widens to about 80 cm^{-1} . The spectra at the bias of highest WPE is perfectly centered around the design wavelength of $8\text{ }\mu\text{m}$. This shows, that considering graded interfaces during the design process enables a reliable prediction of the emission wavelength.³²

4 Detector operation

The detector functionality of the bi-functional device has a similar performance compared to previous designs^{22,23,31} considering the smaller device resistance, which originates from its exponential relation to the photon energy via the activation energy. As pointed out by earlier work, the device resistance is not as crucial due to the geometrical advantage of the end-fire coupled on-chip detector.³¹ Figure 4 shows the detector spectrum compared to the laser emission spectrum. As described above, a small remaining wavelength shift was accepted during design to achieve a better overall performance. Due to the small facet size, the characterization with external sources is possible but challenging because it requires precise knowledge of the beam profile and spectral density to estimate the incident optical power. Here, we use the on-chip configuration where the laser and the detector ridges are separated with a small gap⁴⁴ to obtain the absolute value of the detector responsivity. This approach requires calibration via the coupling efficiency from the laser to the detector as well as the laser output power. These values typically fluctuate much less and can be obtained using a power meter collecting light from the second laser facet and 3D FEM modeling to obtain the reflectivities and the coupling efficiency. Furthermore, the on-chip characterization better represents the configuration used for on-chip sensing applications. Figure 5 shows the signal of the on-chip detector at the back facet compared to a calibrated external detector at the front laser facet. The gap between the laser and the detector can have a strong influence on the laser facet reflectivity. Thus, we measured the gap size using a scanning electron

microscope to be $5.4\,\mu\text{m} \pm 0.1\,\mu\text{m}$ and calculated the laser facet reflectivity from the 3D FEM simulation. From this the power ratio between back and front side laser emission can be calculated to be $r_{21} = P_2/P_1 = \sqrt{R_{\text{laser},1}/R_{\text{laser},2}}(1 - R_{\text{laser},1})/(1 - R_{\text{laser},2}) \approx 0.93 \pm 0.01$. From the 3D FEM simulation we also obtain the coupling factor from the back facet emission to the detector ($\eta_{\text{coupling}} = 0.57 \pm 0.015$). The ratio between the power inside the detector and emitted from the front facet is then $r_{21}\eta_{\text{coupling}} = 0.53 \pm 0.02$. As we consider the detector facet to be a part of the detector, we divide the ratio by the transitivity to obtain the total correction factor $r_{\text{corr}} = r_{21}\eta_{\text{coupling}}/(1 - R_{\text{detector}}) = 0.71 \pm 0.027$. From this quite rigorous approach, we can calculate the responsivity of the on-chip detector at the laser emission wavelength to be $R_{8\,\mu\text{m}} = I_{\text{ph}}/(r_{\text{corr}}P_{\text{meas}}) \approx 14\,\text{mA/W}$ and the peak responsivity to be $R_{\text{peak}} \approx 20\,\text{mA/W}$.

We measured multiple detectors with different ridge lengths (50 μm , 100 μm , 200 μm , 500 μm) to obtain the absorption coefficient at the laser emission wavelength of $\alpha_{8\,\mu\text{m}} = 60\,\text{cm}^{-1}$. Compared to previous devices,^{22,31} the absorption coefficient is lower due to the reduced doping. However, due to the end-fire coupled waveguide detector and the fact that also the waveguide losses are much smaller, the same absorption efficiency can be achieved just by using longer ridges. We calculate the optimal detector ridge length in terms of Johnson noise equivalent power at the laser emission wavelength $\text{NEP}_{8\,\mu\text{m}}^{\text{J}}$ to be 200 μm , with $\text{NEP}_{8\,\mu\text{m}}^{\text{J}} = 0.14\,\text{nW}/\sqrt{\text{Hz}}$. Longer detectors are preferable if the noise of the system is limited by other sources. Here, one can immediately recognize the noise reduction due to the small size as a major advantage over external discrete detectors, beside larger coupling and absorption efficiencies.

5 Conclusion and discussion

With this work we brought bi-functional QCLDs to a new performance level, where in laser operation they can directly compete with conventional QCLs. The on-chip detection

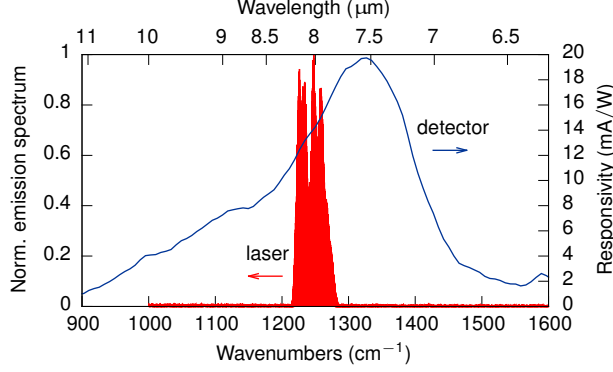


Figure 4: Spectral responsivity of the ridge detector and the normalized laser emission spectrum. A small remaining wavelength-shift was accepted during the design to optimize the overall performance.

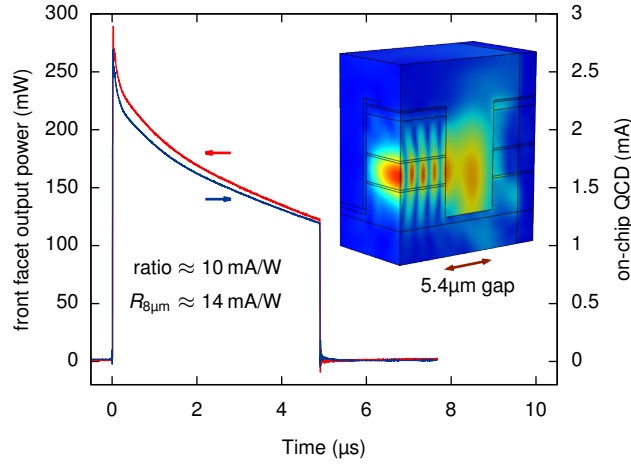


Figure 5: Laser pulse measured the on-chip detector and a calibrated external detector. The laser ridge length for this experiment is significantly smaller and results in a reduced output power. The inset shows the 3D FEM simulation result for the coupling through the 5.4 μm gap.

feature shows high signal-to-noise ratios due to the coupling scheme and enables a straightforward realization of monolithically integrated mid-infrared sensors. The demonstration of continuous-wave operation at 8 μm is an important step to push integrated sensing systems. It shows that the wavelength scalability known from QCLs also applies for bi-functional designs and enables sensing schemes that rely on continuous wave emission due to the required stability. One of the most interesting and prominent techniques is heterodyne detection, which enables phase sensitive detection of extremely small power levels. This makes heterodyne detection attractive for remote sensing and stand-off detection.⁴⁵ This concept is

particularly useful for on-chip integration as detection of the beating between two laser lines is fundamentally insensitive to electric crosstalk between the lasers and detector and can potentially solve current issues of recently presented gas sensors.²⁴ High power local oscillators can be easily realized and directly coupled to the detectors. Going one step further, the heterodyne detection concept can also be applied in parallel at multiple wavelengths. Using frequency combs, an entire spectrum covering several ten to hundred wavenumbers can be acquired with a single shot. Frequency combs have been recently realized using QCL active regions,^{46,47} which, together with the demonstration of continuous wave bi-functional devices, opens the perspective of on-chip dual comb spectroscopy. Also for discrete sensing setups, one can switch to lasers based on bi-functional materials, as they show similar performance but enable integrated power monitoring, stabilization or referencing.

6 Acknowledgements

BS and GS were supported by the Austrian Science Fund (FWF) within the framework of the Doctoral School Solids4Fun (project W1243) and the projects NextLite (F4909-N23) and NanoPlas (P28914-N27). The work conducted by Lincoln Laboratory was sponsored by Assistant Secretary of Defense for Research and Engineering (ASD R&E) under Air Force Contract FA8721-05-C-0002. Opinions, interpretations, conclusions, and recommendations are those of the authors and are not necessarily endorsed by the United States Government.

References

- (1) Chen, S.; Li, W.; Wu, J.; Jiang, Q.; Tang, M.; Shutts, S.; Elliott, S. N.; Sobiesierski, A.; Seeds, A. J.; Ross, I.; Smowton, P. M.; Liu, H. Electrically pumped continuous-wave III–V quantum dot lasers on silicon. *Nature Photonics* **2016**, *10*, 307.
- (2) Vivien, L.; Pavesi, L. *Handbook of silicon photonics*; Taylor & Francis, 2016.

- (3) Pavesi, L.; Lockwood, D. J. *Silicon photonics*; Springer Science & Business Media, 2004; Vol. 1.
- (4) Justice, J.; Bower, C.; Meitl, M.; Mooney, M. B.; Gubbins, M. A.; Corbett, B. Wafer-scale integration of group III–V lasers on silicon using transfer printing of epitaxial layers. *Nature Photonics* **2012**, *6*, 612.
- (5) Spott, A.; Peters, J.; Davenport, M. L.; Stanton, E. J.; Merritt, C. D.; Bewley, W. W.; Vurgaftman, I.; Kim, C. S.; Meyer, J. R.; Kirch, J.; Mawst, L. J.; Botez, D.; Bowers, J. E. Quantum cascade laser on silicon. *Optica* **2016**, *3*, 545.
- (6) Haas, J.; Mizaikoff, B. Advances in Mid-Infrared Spectroscopy for Chemical Analysis. *Annual Review of Analytical Chemistry* **2016**, *9*, 45.
- (7) Cho, A.; Arthur, J. Molecular beam epitaxy. *Progress in Solid State Chemistry* **1975**, *10*, 157.
- (8) Faist, J.; Capasso, F.; Sivco, D. L.; Sirtori, C.; Hutchinson, A. L.; Cho, A. Y. Quantum Cascade Laser. *Science* **1994**, *264*, 553.
- (9) Capasso, F. High-performance midinfrared quantum cascade lasers. *Optical Engineering* **2010**, *49*, 111102.
- (10) Rauter, P.; Capasso, F. Multi-wavelength quantum cascade laser arrays. *Laser & Photonics Reviews* **2015**, *9*, 452.
- (11) Namjou, K.; Cai, S.; Whittaker, E. A.; Faist, J.; Gmachl, C.; Capasso, F.; Sivco, D. L.; Cho, A. Y. Sensitive absorption spectroscopy with a room-temperature distributed-feedback quantum-cascade laser. *Optics Letters* **1998**, *23*, 219.
- (12) Kosterev, A. A.; Curl, R. F.; Tittel, F. K.; Gmachl, C.; Capasso, F.; Sivco, D. L.; Baillargeon, J. N.; Hutchinson, A. L.; Cho, A. Y. Methane concentration and isotopic

- composition measurements with a mid-infrared quantum-cascade laser. *Optics Letters* **1999**, *24*, 1762.
- (13) Paldus, B. A.; Spence, T. G.; Zare, R. N.; Oomens, J.; Harren, F. J. M.; Parker, D. H.; Gmachl, C.; Cappasso, F.; Sivco, D. L.; Baillargeon, J. N.; Hutchinson, A. L.; Cho, A. Y. Photoacoustic spectroscopy using quantum-cascade lasers. *Optics Letters* **1999**, *24*, 178.
- (14) Lendl, B.; Frank, J.; Schindler, R.; Müller, A.; Beck, M.; Faist, J. Mid-Infrared Quantum Cascade Lasers for Flow Injection Analysis. *Analytical Chemistry* **2000**, *72*, 1645.
- (15) Gittins, C. M.; Wetjen, E. T.; Gmachl, C.; Capasso, F.; Hutchinson, A. L.; Sivco, D. L.; Baillargeon, J. N.; Cho, A. Y. Quantitative gas sensing by backscatter-absorption measurements of a pseudorandom code modulated $\lambda \sim 8\text{-}\mu\text{m}$ quantum cascade laser. *Optics Letters* **2000**, *25*, 1162.
- (16) Hofstetter, D.; Beck, M.; Faist, J. Quantum-cascade-laser structures as photodetectors. *Applied Physics Letters* **2002**, *81*, 2683.
- (17) Gendron, L.; Carras, M.; Huynh, A.; Ortiz, V.; Koeniguer, C.; Berger, V. Quantum cascade photodetector. *Applied Physics Letters* **2004**, *85*, 2824.
- (18) Reininger, P.; Zederbauer, T.; Schwarz, B.; Detz, H.; MacFarland, D.; Andrews, A. M.; Schrenk, W.; Strasser, G. InAs/AlAsSb based quantum cascade detector. *Applied Physics Letters* **2015**, *107*, 081107.
- (19) Rogalski, A. HgCdTe infrared detector material: history, status and outlook. *Reports on Progress in Physics* **2005**, *68*, 2267.
- (20) Schneider, H.; Liu, H. C. *Quantum Well Infrared Photodetectors*; Springer, Berlin, 2006.
- (21) Kim, S.-S.; Young, C.; Mizaikoff, B. Miniaturized mid-infrared sensor technologies. *Analytical and Bioanalytical Chemistry* **2008**, *390*, 231.

- (22) Schwarz, B.; Reininger, P.; Detz, H.; Zederbauer, T.; Andrews, A. M.; Kalchmair, S.; Schrenk, W.; Baumgartner, O.; Kosina, H.; Strasser, G. A bi-functional quantum cascade device for same-frequency lasing and detection. *Applied Physics Letters* **2012**, *101*, 191109.
- (23) Schwarz, B.; Reininger, P.; Ristanić, D.; Detz, H.; Andrews, A. M.; Schrenk, W.; Strasser, G. Monolithically integrated mid-infrared lab-on-a-chip using plasmonics and quantum cascade structures. *Nature Communications* **2014**, *5*.
- (24) Harrer, A.; Szedlak, R.; Schwarz, B.; Moser, H.; Zederbauer, T.; MacFarland, D.; Detz, H.; Andrews, A. M.; Schrenk, W.; Lendl, B.; Strasser, G. Mid-infrared surface transmitting and detecting quantum cascade device for gas-sensing. *Sci. Rep.* **2016**, *6*, 21795.
- (25) Szedlak, R.; Harrer, A.; Holzbauer, M.; Schwarz, B.; Wacławek, J. P.; MacFarland, D.; Zederbauer, T.; Detz, H.; Andrews, A. M.; Schrenk, W.; Lendl, B.; Strasser, G. Remote Sensing with Commutable Monolithic Laser and Detector. *ACS Photonics* **2016**, *3*, 1794.
- (26) Bismuto, A.; Terazzi, R.; Hinkov, B.; Beck, M.; Faist, J. Fully automatized quantum cascade laser design by genetic optimization. *Applied Physics Letters* **2012**, *101*, 021103.
- (27) Beck, M. Continuous Wave Operation of a Mid-Infrared Semiconductor Laser at Room Temperature. *Science* **2001**, *295*, 301.
- (28) Bai, Y.; Bandyopadhyay, N.; Tsao, S.; Slivken, S.; Razeghi, M. Room temperature quantum cascade lasers with 27% wall plug efficiency. *Applied Physics Letters* **2011**, *98*, 181102.
- (29) Razeghi, M.; Slivken, S.; Bai, Y.; Gokden, B.; Darvish, S. R. High power quantum cascade lasers. *New Journal of Physics* **2009**, *11*, 125017.

- (30) Xie, F.; Caneau, C.; Leblanc, H. P.; Caffey, D. P.; Hughes, L. C.; Day, T.; en Zah, C. Watt-Level Room Temperature Continuous-Wave Operation of Quantum Cascade Lasers With $\lambda < 10\text{ }\mu\text{m}$. *IEEE Journal of Selected Topics in Quantum Electronics* **2013**, *19*, 1200407.
- (31) Schwarz, B.; Ristanic, D.; Reininger, P.; Zederbauer, T.; MacFarland, D.; Detz, H.; Andrews, A. M.; Schrenk, W.; Strasser, G. High performance bi-functional quantum cascade laser and detector. *Applied Physics Letters* **2015**, *107*, 071104.
- (32) Wang, C.; Schwarz, B.; Siriani, D.; Connors, M.; Missaggia, L.; Calawa, D.; McNulty, D.; Akey, A.; Zheng, M.; Donnelly, J.; Mansuripur, T.; Capasso, F. Sensitivity of Heterointerfaces on Emission Wavelength of Quantum Cascade Lasers. *Journal of Crystal Growth* **2016**,
- (33) Maulini, R.; Lyakh, A.; Tsekoun, A.; Patel, C. K. N. $\lambda \sim 71\text{ }\mu\text{m}$ quantum cascade lasers with 19% wall-plug efficiency at room temperature. *Opt. Express* **2011**, *19*, 17203.
- (34) Lyakh, A.; Maulini, R.; Tsekoun, A.; Go, R.; Patel, C. K. N. Multiwatt long wavelength quantum cascade lasers based on high strain composition with 70% injection efficiency. *Optics Express* **2012**, *20*, 24272.
- (35) Troccoli, M.; Lyakh, A.; Fan, J.; Wang, X.; Maulini, R.; Tsekoun, A. G.; Go, R.; Patel, C. K. N. Long-Wave IR Quantum Cascade Lasers for emission in the $\lambda = 8\text{--}12\text{ }\mu\text{m}$ spectral region. *Optical Materials Express* **2013**, *3*, 1546.
- (36) Bismuto, A.; Terazzi, R.; Beck, M.; Faist, J. Electrically tunable, high performance quantum cascade laser. *Applied Physics Letters* **2010**, *96*, 141105.
- (37) Fujita, K.; Furuta, S.; Sugiyama, A.; Ochiai, T.; Edamura, T.; Akikusa, N.; Yamanishi, M.; Kan, H. High-Performance $\lambda \sim 8.6\text{ }\mu\text{m}$ Quantum Cascade Lasers With Single Phonon-Continuum Depopulation Structures. *IEEE Journal of Quantum Electronics* **2010**, *46*, 683.

- (38) Missaggia, L.; Wang, C.; Connors, M.; Saar, B.; Sanchez-Rubio, A.; Creedon, K.; Turner, G.; Herzog, W. Thermal management of quantum cascade lasers in an individually addressable monolithic array architecture. *Components and Packaging for Laser Systems II*. 2016.
- (39) Baumgartner, O.; Stanojevic, Z.; Kosina, H. In *Monte Carlo Methods and Applications*; Sabelfeld, K. K., Dimov, I., Eds.; De Gruyter Borovets, Bulgaria, 2012; Vol. 59; p 67.
- (40) Carosella, F.; Ndebeka-Bandou, C.; Ferreira, R.; Dupont, E.; Unterrainer, K.; Strasser, G.; Wacker, A.; Bastard, G. Free-carrier absorption in quantum cascade structures. *Physics Review B* **2012**, *85*.
- (41) Beck, M.; Faist, J.; Oesterle, U.; Ilegems, M.; Gini, E.; Melchior, H. Buried heterostructure quantum cascade lasers with a large optical cavity waveguide. *IEEE Photonics Technology Letters* **2000**, *12*, 1450.
- (42) Faist, J. *Quantum Cascade Lasers*; Oxford University press, 2013.
- (43) Botez, D.; Chang, C.-C.; Mawst, L. J. Temperature sensitivity of the electro-optical characteristics for mid-infrared ($\lambda = 3\text{--}16\ \mu\text{m}$)-emitting quantum cascade lasers. *Journal of Physics D: Applied Physics* **2016**, *49*, 043001.
- (44) Schwarz, B.; Reininger, P.; Detz, H.; Zederbauer, T.; Andrews, A.; Schrenk, W.; Strasser, G. Monolithically Integrated Mid-Infrared Quantum Cascade Laser and Detector. *Sensors* **2013**, *13*, 2196.
- (45) Wang, Y.; Soskind, M. G.; Wang, W.; Wysocki, G. High-resolution multi-heterodyne spectroscopy based on Fabry-Perot quantum cascade lasers. *Applied Physics Letters* **2014**, *104*, 031114.
- (46) Hugi, A.; Villares, G.; Blaser, S.; Liu, H. C.; Faist, J. Mid-infrared frequency comb based on a quantum cascade laser. *Nature* **2012**, *492*, 229.

- (47) Villares, G.; Hugi, A.; Blaser, S.; Faist, J. Dual-comb spectroscopy based on quantum-cascade-laser frequency combs. *Nature Communications* **2014**, *5*, 5192.

Graphical TOC Entry

